

Concepts of Object-Oriented Programming

Peter Müller

Chair of Programming Methodology

Autumn Semester 2016

ETH zürich

Meeting the Requirements

Cooperating Program Parts with Well-Defined Interfaces

- Objects (data + code)
- Interfaces
- Encapsulation

Classification and Specialization

- Classification, subtyping
- Polymorphism
- Substitution principle

Highly Dynamic Execution Model

- Active objects
- Message passing

Correctness

- Interfaces
- Encapsulation
- Simple, powerful concepts

Topics in this Section

- Cooperating program parts ...
 - How do we define components?
- ... with well-defined interfaces
 - What is the interface of a component?
 - How do we describe the interface of a component?
 - How do we make sure clients use a component correctly?



Types
and
contracts

4. Types

4.1 Bytecode Verification

4.2 Parametric Polymorphism

Mobile Code: Motivation

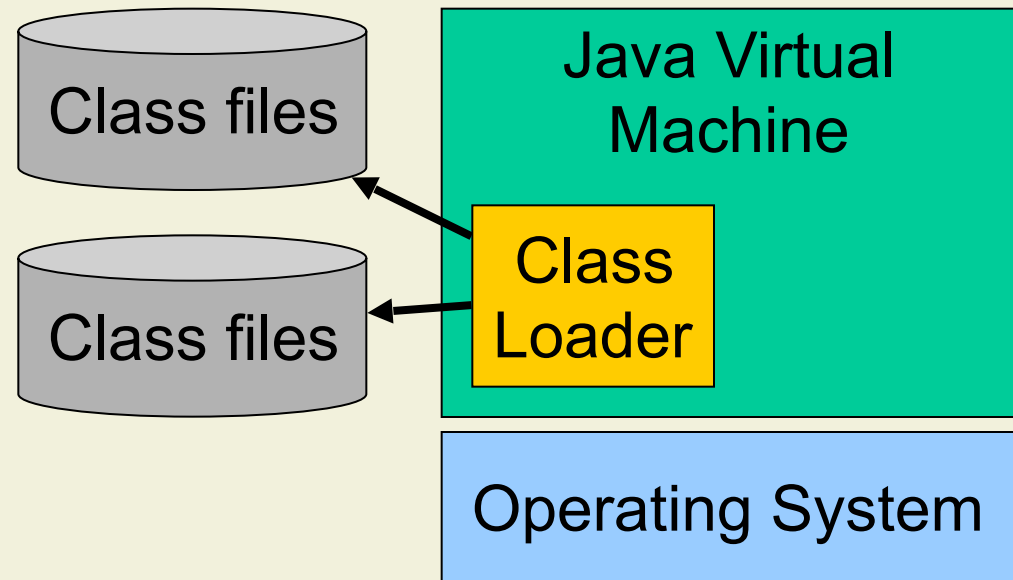
- Download and execution of code, e.g., Java applets
 - Web pages
 - Mobile devices

- Upload of code
 - Customizing servers

- Automatic distribution of code and patches in distributed systems

Class Loaders

- Programs are compiled to bytecode
 - Platform-independent format
 - Organized into class files
- Bytecode is interpreted on a virtual machine
- Class loader gets code for classes and interfaces on demand
- Programs can contain their own class loaders



Example: Specialized Class Loader

Error
handling
partly
omitted

```
public class MyLoader extends ClassLoader {  
    byte[ ] getClassData( String name ) { ... }  
  
    public synchronized Class loadClass( String name )  
        throws ClassNotFoundException {  
  
        Class c = findLoadedClass( name );  
        if ( c != null ) return c;  
  
        try { c = findSystemClass( name ); return c; }  
        catch ( ClassNotFoundException e ) { }  
  
        byte[ ] data = getClassData( name );  
        return defineClass( name, data, 0, data.length ); }  
}
```

Java

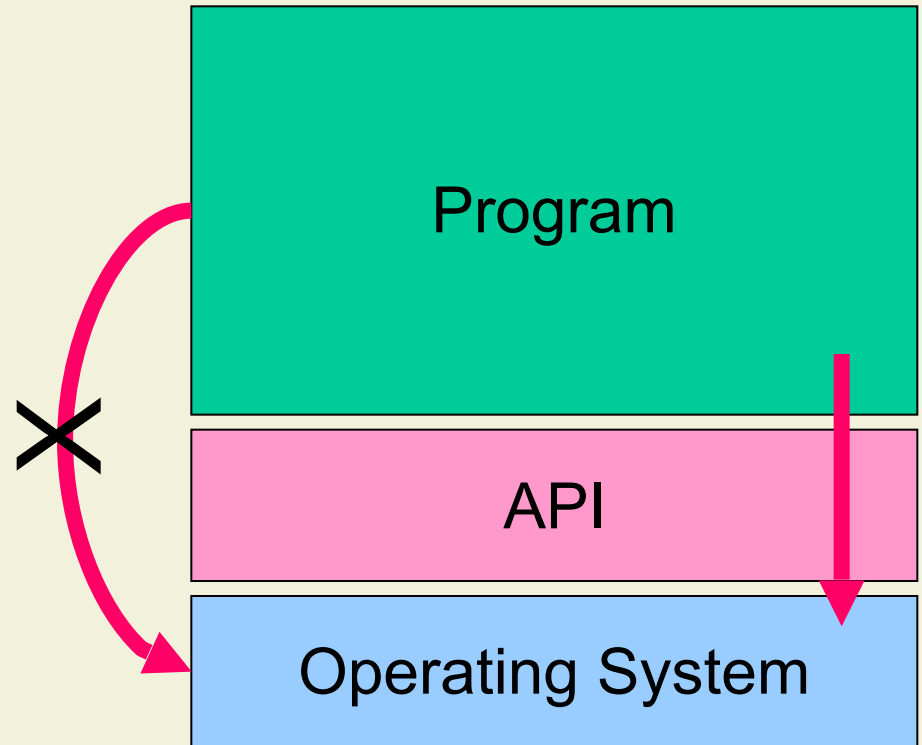
Security for Java Programs

■ Sandbox

- Applets get access to system resources only through an API
- Access control can be implemented

■ Security relies on

- Type safety
- Code does not by-pass sandbox



Security in Mobile Environments

■ Mobile code cannot be trusted

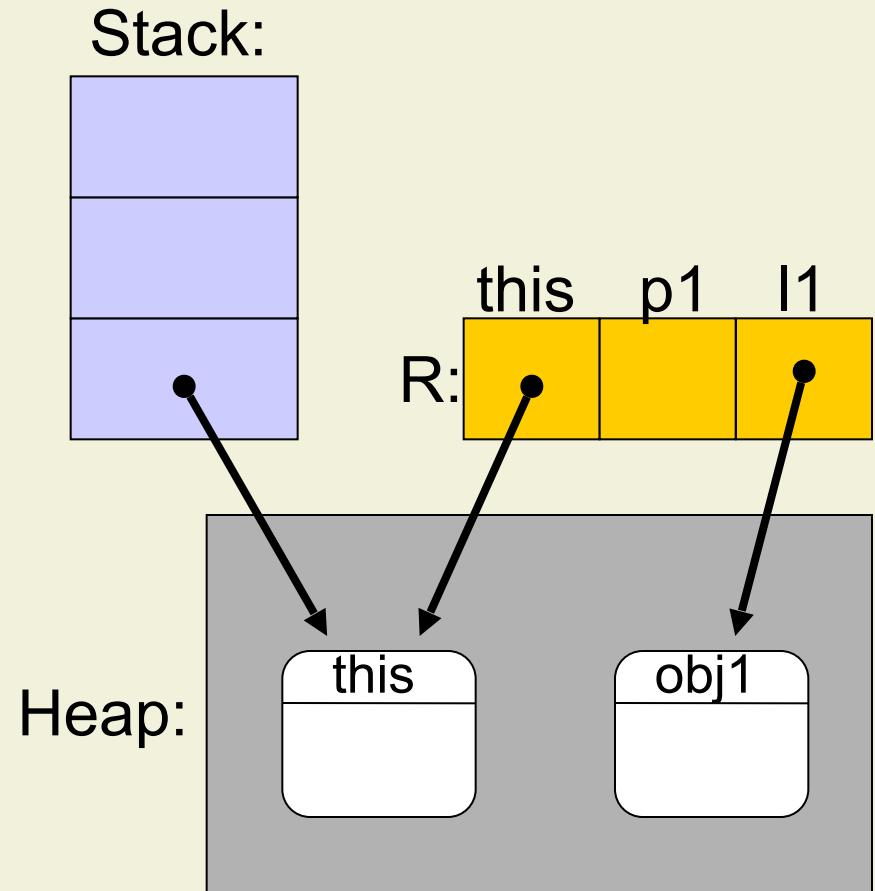
- Code may not be type safe
- Code may destroy or modify data
- Code may expose personal information
- Code may crash the underlying VM
- Code may purposefully degrade performance (denial of service)

■ How to guarantee a minimum level of security?

- Untrusted code producer
- Untrusted compiler

Java Virtual Machine

- JVM is stack-based
- Most operations pop operands from a stack and push a result
- Registers store method parameters and local variables
- Stack and registers are part of the method activation record



Java Bytecode

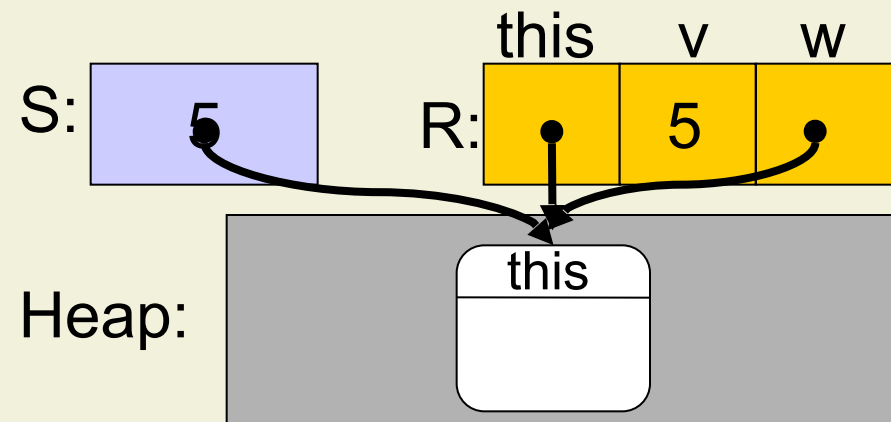
- Instructions are typed
- Load and store instructions access registers
- Control is handled by intra-method branches (goto, conditional branches)

```

class C {
  void m( ) {
    int v;
    Object w;
    v = 5;
    w = this;
  }
}
    
```

```

iconst 5
istore 1
aload 0
astore 2
return
    
```



Bytecode Verification

- Proper execution requires that
 - Each instruction is type correct
 - Only initialized variables are read
 - No stack over- or underflow occurs
 - Etc.

- Java Virtual Machine guarantees these properties
 - By **bytecode verification** when a class is loaded
 - By **dynamic checks at run time**

Bytecode Verification via Type Inference

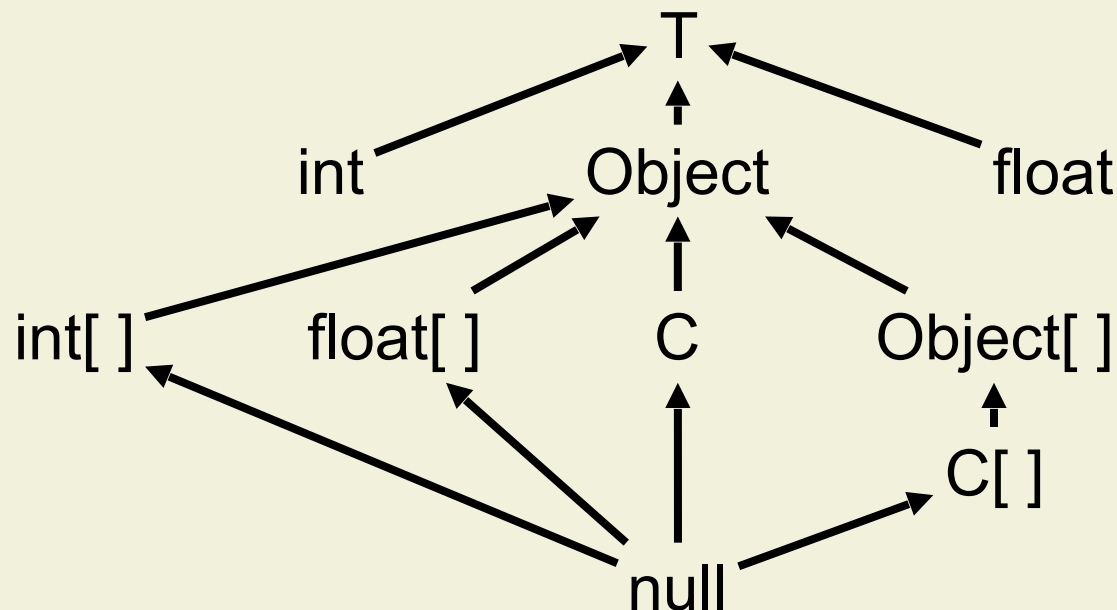
- The Bytecode verifier **simulates** the execution of the program
- Operations are performed on **types instead of values**
- For each instruction, a rule describes how the **operand stack and local variables** are modified

$$\begin{aligned} i: (S, R) &\rightarrow (S', R') \\ \text{iadd}: (\text{int.int.S}, R) &\rightarrow (\text{int.S}, R) \end{aligned}$$

- Errors are denoted by the **absence of a transition**
 - Type mismatch
 - Stack over- or underflow

Types of the Inference Engine

- Primitive types
- Object and array reference types
- null type for the null reference
- T for uninitialized registers



Selected Rules

- Maximum stack size (MS) and maximum number of parameters and local variables (MR) are stored in the classfile
- Rule for method invocation uses method signature (no jump)

iconst n:

$(S, R) \rightarrow (\text{int}.S, R)$, if $|S| < MS$

iload n:

$(S, R) \rightarrow (\text{int}.S, R)$,
if $0 \leq n < MR \wedge R(n) = \text{int} \wedge |S| < MS$

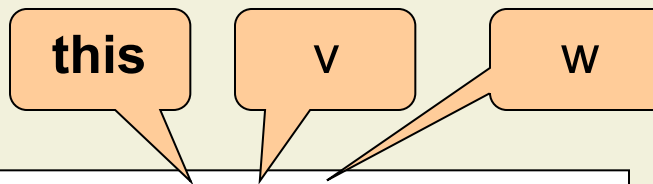
astore n:

$(t.S, R) \rightarrow (S, R\{n \leftarrow t\})$,
if $0 \leq n < MR \wedge t <: \text{Object}$

invokevirtual C.m. σ :

$(t'_n \dots t'_1.t'.S, R) \rightarrow (r.S, R)$, if
 $\sigma = r(t_1, \dots, t_n) \wedge t' <: C \wedge t'_i <: t_i$

Example



```
int v;  
Object w;  
v = 5;  
w = this;
```

```
iconst 5  
istore 1  
aload 0  
astore 2  
return
```

```
( [ ] , [ C,T,T ] ) →  
( int , [ C,T,T ] ) →  
( [ ] , [ C,int,T ] ) →  
( C , [ C,int,T ] ) →  
( [ ] , [ C,int,C ] )
```

```
int v;  
Object w;  
v = 5;  
w = v;
```

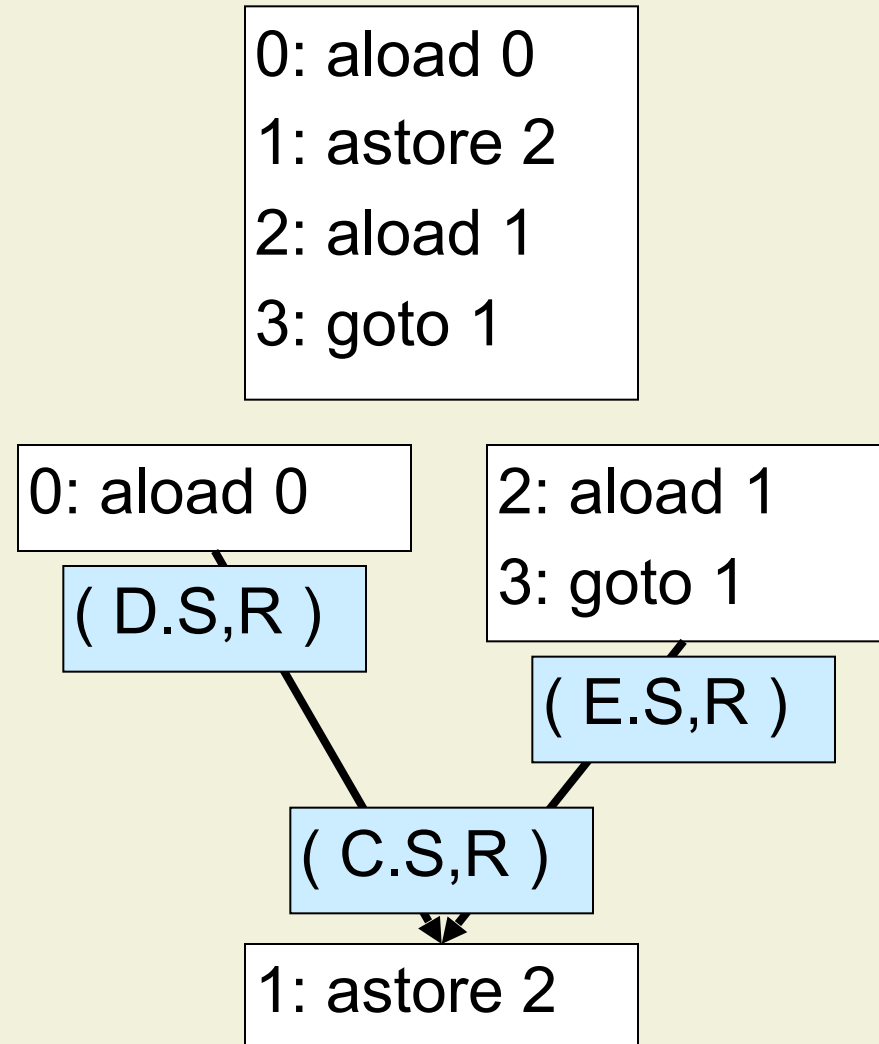
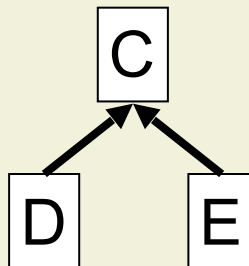
```
iconst 5  
istore 1  
iload 1  
astore 2  
return
```

```
( [ ] , [ C,T,T ] ) →  
( int , [ C,T,T ] ) →  
( [ ] , [ C,int,T ] ) →  
( int , [ C,int,T ] )  
stuck
```

astore
expects an
object type
on top of
the stack!

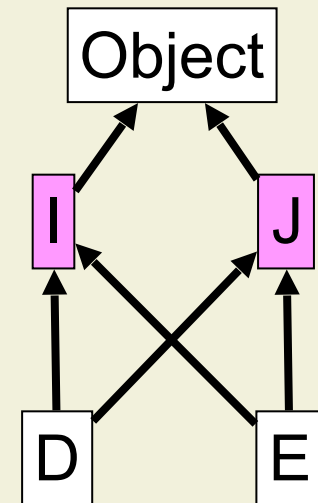
Smallest Common Supertype

- Branches lead to **joins** in control flow
- Instructions can have **several predecessors**
- **Smallest common supertype** is selected (T if no other common supertype exists)



Handling Multiple Subtyping

- With multiple subtyping, **several smallest common supertypes** may exist
- JVM solution
 - Ignore interfaces
 - Treat all interface types as Object
 - Works because of single inheritance of classes
- Problem
 - **invokeinterface** I.m cannot check whether target object implements I
 - Run-time check is necessary



Inference Algorithm

- Inference is a fixpoint iteration

```
in( 0 ) := ( [ ] , [ P0,...,Pn,T,...,T ] )  
worklist := { i | instri is an instruction of the method }  
while worklist ≠ ∅ do  
  i := min( worklist )  
  remove i from worklist  
  out( i ) := apply_rule( instri, in( i ) )  
  foreach q in successors( i ) do  
    in( q ) := pointwise_scs( in( q ), out( i ) )  
    if in( q ) has changed then worklist := worklist ∪ { q }  
  end  
end
```

Pointwise SCS

- $\text{scs}(s, t)$ is the smallest common supertype of s and t

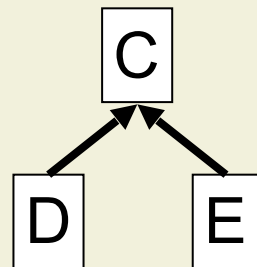
$$\begin{aligned} \text{pointwise_scs} \big(& ([s_1, \dots, s_k], [t_0, \dots, t_n]), \\ & ([s'_1, \dots, s'_k], [t'_0, \dots, t'_n]) \big) = \\ & ([\text{scs}(s_1, s'_1), \dots, \text{scs}(s_k, s'_k)], [\text{scs}(t_0, t'_0), \dots, \text{scs}(t_n, t'_n)]) \end{aligned}$$

- `pointwise_scs` is undefined for stacks of different heights
 - Bytecode verification results in an error

Inference Example

```

0: aload 0
1: astore 2
2: aload 1
3: goto 1
    
```



worklist

0 1 2 3

	in	out
0:	$([], [D, E, T])$	$([D], [D, E, T])$
1:	$([D], [D, E, T])$ $([C], [D, E, T])$ $([C], [D, E, T])$	$([], [D, E, D])$ $([], [D, E, C])$
2:	$([], [D, E, D])$ $([], [D, E, C])$	$([E], [D, E, D])$ $([E], [D, E, C])$
3:	$([E], [D, E, D])$ $([E], [D, E, C])$	$([E], [D, E, D])$ $([E], [D, E, C])$

Type Inference: Discussion

■ Advantages

- Determines the **most general solution** that satisfies the typing rules
- Might be more general than what is permitted by compiler
- Very little type information required in class file

■ Disadvantages

- Fixpoint computations may be slow
- Solution for interfaces is **imprecise** and **requires run-time checks**

■ Alternative: type checking (since Java 6)

Bytecode Verification via Type Checking

- Extend class file to store type information

([int] , [C,int,T])

- Type information can be declared for each bytecode instruction
- Type information **required** at the beginning of all **basic blocks**:
 - At jump target
 - At entry point of exception handler
- Computation of SCS no longer necessary
 - Avoid fixpoint computation and interface problem

} Includes
all join points

Type Checking Algorithm

- Use and check declared types wherever available
- Infer types otherwise

foreach basic block of a method body **do**

in := types(start)

foreach { i | instr_i is an instruction of basic block } **do**

in := apply_rule(instr_i, in)

foreach q in successors(i) **do**

if types(q) is declared **then**

check that in is assignable to types(q)

end

end

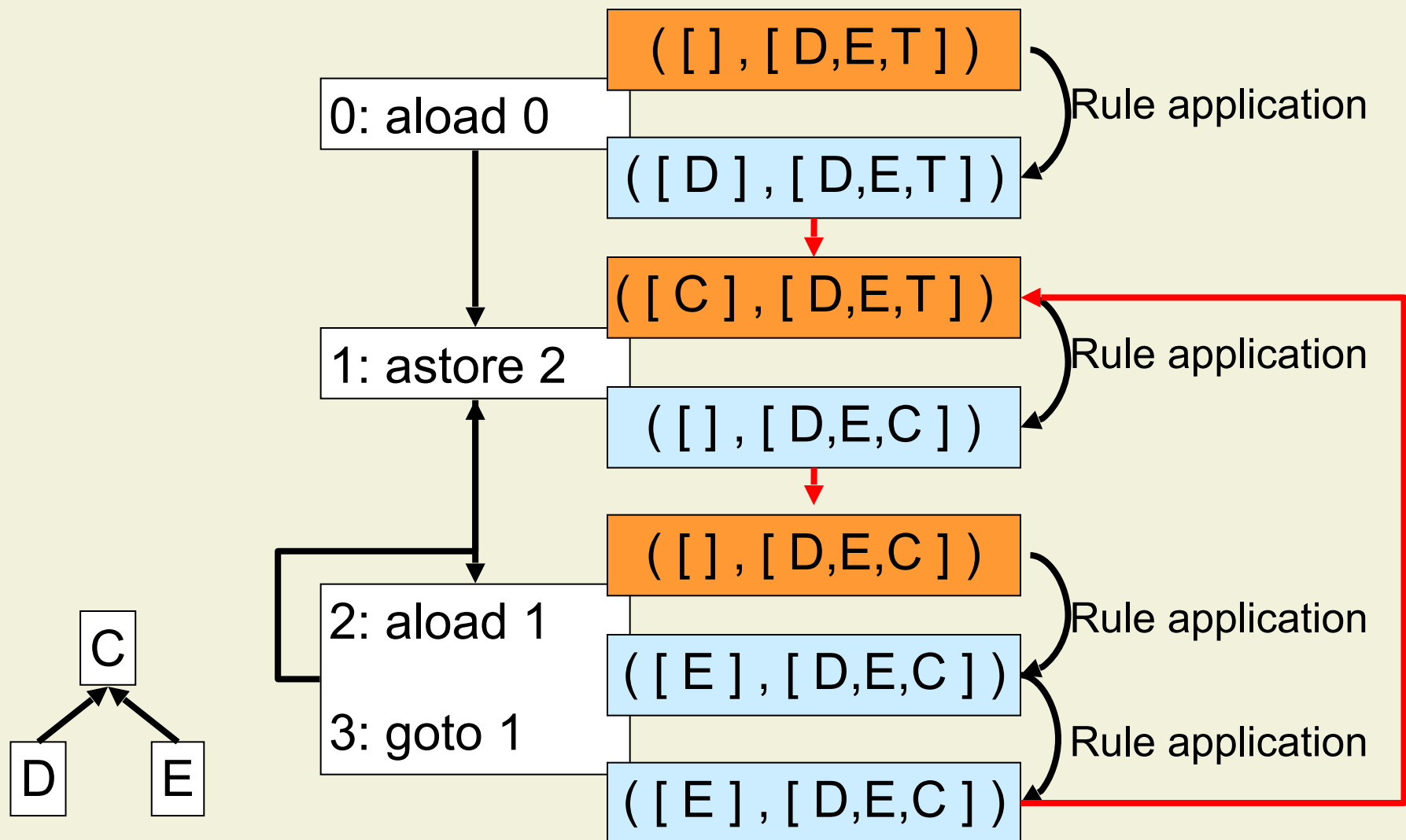
end

Required
types

Check conditions and infer
next configuration

Check
declared types

Type Checking Example



Bytecode Verification: Summary

- Bytecode verification enables secure mobile code
 - For programs written in typed bytecode
- Bytecode verification can be done via **type inference** or **type checking**
- Some run-time type checks are still necessary
 - For instance, casts and co-variant arrays

Type Inference for Source Programs

- Type inference can also be done on source code
 - For example, C# 3.0 and Scala **infer types of local variables**
 - **Reduce annotation overhead**, especially with generics
- Type annotations can still be used to support inference

```
def sum( a: Array[ Int ] ): Int = {  
  val it = a.elements  
  var s = 0;  
  while( it.hasNext ) { s = s + it.next }  
  s  
}
```

Scala

```
def client = {  
  var a = 1  
  a = "Hello"  
}
```

Scala

```
def client = {  
  var a: Any = 1  
  a = "Hello"  
}
```

Scala

Type Inference vs. Dynamic Typing

- Type inference determines the static type automatically and then performs static type checking
- Dynamic typing does not require a static type and does not perform static type checking

```
void client( ) {  
    var a = 1;  
    a = "Hello";  
}
```

C#

```
void client( ) {  
    dynamic a = 1;  
    a = "Hello";  
}
```

C#

Inference of Method and Field Types

- Inference of method signatures generally requires knowledge of all implementations
- Inference of field types generally requires knowledge of all assignments to the field
- Inference of these types is non-modular
 - Or based on speculation

```
class A {
  var f = 5;
  def foo( p: Int ) = {
    p
  }
}
```

Inference: f: Int

Inference: foo returns Int

```
class B extends A {
  f = "Hello";
  override def foo( p: Int ) = {
    "Hello"
  }
}
```

Scala

4. Types

4.1 Bytecode Verification

4.2 Parametric Polymorphism

Polymorphism Revisited

- Not all polymorphic code is best expressed using subtype polymorphism
- Recovering precise type information requires **downcasts**
- Subtype relations are sometimes **not desirable**
 - E.g., covariant arrays

```
class Queue {  
    Object elem;  
    Queue next;  
    void enqueue( Object e ) { ... }  
    Object dequeue( ) { ... }  
}
```

Java

```
Queue q = new Queue( );  
String s = "Hello";  
q.enqueue( s );  
String t = ( String ) q.dequeue( );
```

Java

```
static void fill( Object[ ] a, Object val )  
{ ... }
```

Java

Parametric Polymorphism

- Classes and methods can be **parameterized with types**
- Clients provide instantiations for type parameters
- **Modularity**: generic code is type checked once and for all (without knowing the instantiations)

```
class Queue<T> {  
    T elem;  
    Queue<T> next;  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

Java

```
Queue<String> q;  
q = new Queue<String>( );  
String s = "Hello";  
q.enqueue( s );  
String t = q.dequeue( );
```

Java

```
static <T> void fill( T[ ] a, T val )  
{ ... }
```

Java

Type Checking Generic Code

- Type checking a generic class often **requires information about its type arguments**
 - Availability of methods
- Constraints can be expressed by specifying **upper bounds** on type parameters

```
class Queue<T> {  
    T elem;  
    Queue<T> next;  
  
    void enqueue( T e ) {  
        if( next == null ) { ... }  
        else {  
            if( e.compareTo( elem ) <= 0 ) {  
                next.enqueue( elem );  
                elem = e;  
            } else next.enqueue( e );  
        }  
    }  
    ...  
}
```

Java

Upper Bounds: Example

```
interface Comparable<T> {  
    int compareTo( T o );  
}
```

Java

```
Queue<String> q;  
// String implements  
    Comparable<String>
```

Java

```
Queue<Person> q;  
// Person does not implement  
    Comparable<Person>
```

Java

```
class Queue<T extends Comparable<T>> {  
    T elem;  
    Queue<T> next;  
  
    void enqueue( T e ) {  
        if( next == null ) { ..  
        else {  
            if( e.compareTo( elem ) <= 0 ) {  
                next.enqueue( elem );  
                elem = e;  
            } else next.enqueue( e );  
        }  
    }  
    ...  
}
```

Typecheck under the
assumption
T <: Comparable<T>

Java

Subtyping and Generics

```
class Queue<T extends Comparable<T>> { ... }
```

- Generic types are subtypes of their declared supertypes
- Type variables are subtypes of their upper bounds
- How about different instantiations of the same generic class?

```
Object o = new Queue<String>( );
```

```
void foo( T p ) {  
    Comparable<T> v = p;  
}
```

```
List<Person> o;  
o = new List<Student>( );  
o = new List<Object>( );
```

Covariant Type Arguments

- Covariance:
If $S \leq T$ then
 $C<S> \leq C<T>$
- Covariance is unsafe
when a generic type
argument is used for
variables that are written
by clients
 - Mutable fields
 - Method arguments

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

```
void put( Queue<Object> q ) {  
    q.enqueue( "Hello" );  
}
```

Not type safe if q had
type Queue<Integer>

```
Object get( Queue<Object> q ) {  
    return q.dequeue( );  
}
```

Contravariant Type Arguments

- Contravariance:

If $S \leq T$ then

$C\langle T \rangle \leq C\langle S \rangle$

- Contravariance is unsafe when a generic type argument is used for variables that are read by clients

- Fields
- Method results

```
class Queue<T> {
    void enqueue( T e ) { ... }
    T dequeue( ) { ... }
}
```

```
void put( Queue<String> q ) {
    q.enqueue( "Hello" );
}
```

```
String get( Queue<String> q ) {
    return q.dequeue( );
}
```

Not type safe if q had type Queue<Object>

Java/C# Solution: Non-Variance

- Generic types in Java/C# are **non-variant** (neither covariant nor contravariant)
- Non-variance is **statically type safe**
 - No run-time checks needed
- Non-variance is sometimes overly restrictive

```
class Queue<T> {  
    void enqueue( T e ) { ... }  
    T dequeue( ) { ... }  
}
```

Java

```
Queue<Object> o;  
o = new Queue<String>( );
```

Java

```
Queue<String> o;  
o = new Queue<Object>( );
```

Java

```
class Random<T> {  
    T next( ) { ... }  
}
```

Java/C#: Generics vs. Arrays

- Recall: Java/C# arrays are covariant
- But an array `T[]` is not much different from a class `Array<T>`

```
Object[ ] o;  
o = new String[ 5 ];
```

Java

```
Queue<Object> o;  
o = new Queue<String>( );
```

Java

- Run-time checks
 - Covariant arrays require run-time checks for each update
 - Covariant generics would need checks for field updates and argument passing
- Covariant generics would require more run-time checks in more bytecode instructions

Eiffel Solution: Covariance

- Generic types in Eiffel are **covariant**
- Design is consistent with covariance for method arguments and fields
 - But **not statically type safe**

```
class Queue[ T ] ... end
```

Eiffel

```
o: Queue[ ANY ]  
s: Queue[ STRING ]  
create s.make  
o := s
```

Eiffel

```
o: Queue[ ANY ]  
s: Queue[ STRING ]  
create o.make  
s := o
```

Eiffel

Scala Solution: Variance Annotations

- By default, generic types in Scala are **non-variant**
- Programmers can supply **variance annotations** to allow co- and contravariance
- Type checker imposes **restrictions** on use of variance annotations

```
class Queue[ T ] {  
  def enqueue( e: T ) = { ... }  
  def dequeue: T = { ... }  
}
```

Scala

```
Queue[ AnyRef ] o;  
o = new Queue[ String ]( );
```

Scala

```
Queue[ String ] o;  
o = new Queue[ AnyRef ]( );
```

Scala

Covariance Annotations

- A covariance annotation (+) is useful when type variable occurs **only in positive positions**

- Result type
- Types of immutable fields

- Type checker prevents other occurrences

```
class Random[ +T ] {  
  def next: T = { ... }  
}
```

Scala

```
val r: Random[ AnyRef ] =  
    new Random[ String ]( )  
val a = r.next
```

Scala

```
class Random[ +T ] {  
  def next: T = { ... }  
  def initialize( i: T ) = { ... }  
}
```

Scala

Contravariance Annotations

- A contravariance annotation (-) is useful when type variable occurs **only in negative positions**
 - Parameter type
- Type checker prevents other occurrences

```
class OutputChannel[ -T ] {  
  def write( x: T ) = { ... }  
}
```

Scala

```
val o: OutputChannel[ String ] =  
  new OutputChannel[ AnyRef ]( )  
o.write( "Hello" )
```

Scala

```
class OutputChannel[ -T ] {  
  def write( x: T ) = { ... }  
  def lastWritten: T = { ... }  
}
```

Scala

Working with Non-Variant Generics

- How can we write code that works with many different instantiations of a generic class?
- Solution 1: Method type arguments

```
static <T> void printAll( Collection<T> c ) {  
    for ( T e : c ) { System.out.println( e ); }  
}
```

Java

- Solution 2: Wildcards

```
static void printAll( Collection<?> c ) {  
    for ( Object e : c ) { System.out.println( e ); }  
}
```

Java

Wildcards and Existential Types

- A wildcard represents an **unknown type**

```
static void printAll( Collection<?> c ) {  
    for ( Object e : c ) { System.out.println( e ); }  
}
```

Java

- Interpretation as **existential type**
 - “There exists a type argument T such that c has type Collection<T>”
 - Existential quantifier is instantiated automatically by the type system

```
Collection<String> c = new ArrayList<String>( );  
...  
printAll( c );
```

Wildcard instantiated
with String

Java

Wildcard Examples

Correct: type checker
instantiates type argument
with c's type argument

```
static Collection<?> id( Collection<?> c ) {  
    return c;  
}
```

Two existential
types

```
Collection<String> c = new ArrayList<String>( );  
Collection<String> d = id( c );
```

Type error: existential
types might have
different instantiations
(modular type checking)

Wildcard Examples (cont'd)

```
static void merge( Collection<?> c, Collection<?> d ) {  
    for( Object e : c ) { d.add( e ); }  
}
```

Two existential
types

Type error: d might
expect elements of
different type

Wildcard Examples (cont'd)

```

class Spooler {
    Collection<?> task;

    void setTask( Collection<?> c ) {
        task = c;
    }

    void print( ) {
        for ( Object e : task ) { System.out.println( e ); }
    }
}
    
```

Cannot be simulated
with method type
parameters

Correct: type checker
instantiates task's type
argument with c's

Works because every
Java object has
toString method

Constrained Wildcards

```
static void printFormatted( Collection<?> c ) {  
    for ( Object e : c ) {  
        String s = e.format( 80 );  
        System.out.println( s );  
    }  
}
```

Type error: elements
might not support
method format

Constrained Wildcards: Upper Bounds

```

interface Format {
    String format( int width );
}
    
```

```

static void printFormatted( Collection<? extends Format> c ) {
    for ( Format e : c ) {
        String s = e.format( 80 );
        System.out.println( s );
    }
}
    
```

Typecheck under the
assumption
? <: Format

```

Collection<Object> c = new ArrayList<Object>( );
printFormatted( c );
    
```

Compile-time error: Object
is not a subtype of the
upper bound Format

More Bounded Wildcards

```
class Cell<T> {
    T value;

    void copyFromT( Cell<T> other ) {
        value = other.value;
    }

    void copyFrom( Cell<? extends T> other ) {
        value = other.value;
    }

    void copyTo( Cell<? super T> other ) {
        other.value = value;
    }
}
```

Typecheck under
the assumption

$? <: T$

Typecheck under
the assumption

$T <: ?$

Wildcard can
also have **lower
bounds**

Wildcards vs. Additional Type Parameters

- Often wildcards can be replaced by additional class or method type arguments
 - C# does not have wildcards

```
static <T> void printAll( Collection<T> c ) {  
    for ( T e : c ) { System.out.println( e ); }  
}
```

Java

```
static void printAll( Collection<?> c ) {  
    for ( Object e : c ) { System.out.println( e ); }  
}
```

Java

Wildcards vs. Method Type Parameters

```
void copyFrom( Cell<? extends T> other ) {  
    value = other.value;  
}
```

```
<S extends T> void copyFrom( Cell<S> other ) {  
    value = other.value;  
}
```

```
void copyTo( Cell<? super T> other ) {  
    other.value = value;  
}
```

```
<S super T> void copyTo( Cell<S> other ) {  
    other.value = value;  
}
```

Java does not support
lower bounds for type
parameters

```
Cell<String> s;  
Cell<Object> o;  
s = new Cell<String>();  
o = new Cell<Object>();  
o.copyFrom( s );
```

Identical client code:
instantiations of
wildcard and method
type argument are
inferred

Wildcards vs. Class Type Parameters

```
class Wrapper {  
    Cell<?> data;  
}
```

Instantiation can
change over time

```
Wrapper w = new Wrapper( );  
w.data = new Cell<String>( );  
w.data = new Cell<Object>( );
```

```
class Wrapper<T> {  
    Cell<T> data;  
}
```

```
Wrapper<Object> w = new Wrapper<Object>( );  
w.data = new Cell<String>( );  
w.data = new Cell<Object>( );
```

With type argument,
instantiation is fixed
when object is created

Wildcards vs. Type Parameters (cont'd)

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<E> {  
    TreeSet( Comparator<E> c ) { ... }  
    ... }
```

TreeSet needs to
compare set elements

```
class Person { ... }
```

```
class Student extends Person { ... }
```

```
class PersonComp implements Comparator<Person> {  
    int compare( Person fst, Person snd ) { ... }  
}
```

Universal comparator
for all persons

```
TreeSet<Student> s = new TreeSet<Student>( new PersonComp() );
```

Compile-time error: PersonComp is not
a subtype of Comparator<Student>

Wildcards vs. Type Parameters (cont'd)

```
interface Comparator<T> {  
    int compare( T fst, T snd );  
}
```

```
class TreeSet<E> {  
    TreeSet( Comparator<? super E> c ) { ... }  
    ... }
```

TreeSet needs to compare
at least set elements

```
class Person { ... }
```

```
class Student extends Person { ... }
```

```
class PersonComp implements Comparator<Person> {  
    int compare( Person fst, Person snd ) { ... }  
}
```

```
TreeSet<Student> s = new TreeSet<Student>( new PersonComp() );
```

Wildcard instantiated with Person,
which is a supertype of Student

Subtyping and Generics: Wildcards

- The bounds for a wildcard determine the set of possible instantiations

```
Cell<? extends Person> c;  
Cell<? super PhDStudent> d;
```

- For types S and T with the same class or interface, S is a subtype of T if for each type argument, the set of possible instantiations for S is a subset of the set of possible instantiations for T

```
c = new Cell<Student>( );
```

Instantiation is fixed
(singleton set)

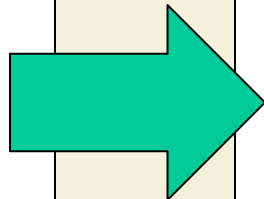
```
Cell<? extends Student> e = ...;  
c = e;
```

Type Erasure

- Java introduced generics in version 1.4
- For **backwards compatibility**, Sun did not want to change the virtual machine
- **Generic type information is erased** by compiler
 - $C<T>$ is translated to C
 - T is translated to its upper bound
 - Casts are added where necessary
- Only one classfile and only one class object to represent all instantiations of a generic class

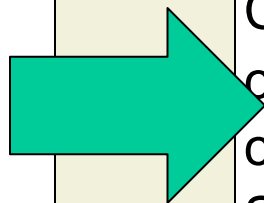
Type Erasure: Example

```
class Cell<T extends Object> {  
    T value;  
  
    void set( T v ) {  
        value = v;  
    }  
  
    T get( ) {  
        return value;  
    }  
}
```



```
class Cell {  
    Object value;  
  
    void set( Object v ) {  
        value = v;  
    }  
  
    Object get( ) {  
        return value;  
    }  
}
```

```
Cell<String> c;  
c = new Cell<String>( );  
c.set( "Hello" );  
String s = c.get( );
```



```
Cell c;  
c = new Cell( );  
c.set( "Hello" );  
String s = ( String ) c.get( );
```

Erasure: Missing Run-Time Information

```
void foo( Cell<?> c ) {  
    if( c instanceof Cell<String> )  
        ...  
}
```

Java

Compile-time error:
generic types not allowed
with **instanceof**

```
Class c = Cell<String>.class;
```

Java

Compile-time error:
class object of generic
types not available

```
Cell<String>[ ] a;  
a = new Cell<String>[10];
```

Java

Compile-time error:
arrays of generic types
not allowed

Run-Time Information for Generics in C#

```
void Foo( object c ) {  
    if( c is Cell<string> )  
        ...  
}
```

C# does not
have wildcards

C# can perform
dynamic type test

C#

```
System.Type type = typeof( Cell<string> );
```

C# has run-time
representation

```
Cell<String>[ ] a;  
a = new Cell<string>[10];
```

C# can perform run-time
check for array update

Erasure: Missing Run-Time Checks

```
String demo( Cell<?> c ) {
    Cell<String> cs = ( Cell<String> ) c;
    ...
    return cs.value;
}
```

Run-time error:
cs.value is not a
string

No run-time
check for this
cast!

Weak type invariant:
object in cs is not of
type Cell<String>!

```
void main( ) {
    Cell<Object> co = new Cell<Object>( );
    co.value = new Integer( 5 );
    demo( co );
}
```

Java

Erasure: Static Fields

- Static fields are shared by all instantiations of a generic class

```
class Count<T> {  
    static int c = 0;  
}
```

```
Count<string>.c = 1;  
Count<object>.c = 2;
```

C#

```
Count.c = 1;  
Count.c = 2;
```

Java

C++ Templates

- Templates allow classes and methods to be **parameterized**
- Clients provide instantiations for template parameters

```
template<class T> class Queue {  
    T elem;  
    Queue<T>* next;  
public:  
    void enqueue( T e ) { ... };  
    T dequeue( void ) { ... };  
};
```

C++

```
Queue<int> *q;  
q = new Queue<int>( );  
int s = 5;  
q->enqueue( s );  
int t = q->dequeue( );
```

C++

```
template<class T> void fill( T a[ ], T v )  
{ ... };
```

C++

Template Instantiation

```

template<class T> class Queue {
    T elem;
    Queue<T>* next;
    ...
};
    
```

Compiler generates class for given template instantiation

```

class Queueint {
    int elem;
    Queueint* next;
    ...
};
    
```

Type checking is done for generated class, not for template

```

Queue<int> *q;
...
    
```

Template Instantiation

```

Queueint *q;
...
    
```

Client code uses generated class

Templates and Type Checking

```
template<class T> class Queue {
    T elem; Queue<T>* next;
public:
    void enqueue( T e ) {
        if( next == NULL ) {
            elem = e; next = new Queue<T>( );
        } else {
            if( e.compareTo( elem ) <= 0 )
            { next->enqueue( elem ); elem = e; }
            else next->enqueue( e );
        }
    };
    T dequeue( void ) { return "Hello"; };
};
```

Compiler does not
check availability
of methods

Compiler does not type
check template code

```
Queue<int> *q;
q = new Queue<int>( );
```

Compiles even
though template is
instantiated

Compile-time errors:
template methods not
type correct

```
Queue<int> *q;
q = new Queue<int>( );
int s = 5;
q->enqueue( s );
int t = q->dequeue( );
```

Templates and Type Checking (cont'd)

- Template code is type checked when instantiated
 - Type errors are not detected before instantiation
- No need for upper bounds on type parameters
 - Availability of methods is not checked anyway
 - Template has to document (informally) what it expects from its type arguments
- Different instantiations of templates are unrelated
 - Use template methods to write polymorphic methods
- Templates do not require run-time support
 - Run-time types correspond to generated classes

Template Meta-Programming

```
template<int n> class Fact {  
public:  
    static const int val = Fact<n-1>::val * n;  
};
```

Template parameters
need not be types

```
template<> class Fact<0> {  
public:  
    static const int val = 1;  
};
```

Templates can be
specialized

Compiler generates
these instantiations

Through constant
propagation, values
are **computed by
compiler**

```
int main( ) {  
    printf( "fact 3 = %d\n", Fact<3>::val );  
    printf( "fact 4 = %d\n", Fact<4>::val );  
    printf( "fact 5 = %d\n", Fact<5>::val );  
    return 0;  
}
```

Generic Types vs. Templates: Summary

Generic Types

- **Modular type checking** of generic class
 - Overhead (e.g., upper bounds)
- **Run-time support** desirable
- No meta-programming

Templates

- Type checking per instantiation
 - Flexibility like with structural typing
- No need for run-time support
- **Meta-programming** is Turing-complete

References

- Xavier Leroy: *Java Bytecode Verification: Algorithms and Formalizations*. Journal of Automated Reasoning, 2003
- Tim Lindholm, Frank Yellin, Gilad Bracha, and Alex Buckley: *The Java Virtual Machine Specification*. 2013
<http://docs.oracle.com/javase/specs/>
- Gilad Bracha, Martin Odersky, David Stoutamire, and Philip Wadler: *Making the Future Safe for the Past: Adding Genericity to the Java Programming Language*. OOPSLA 1998